Improving Energy Density in Biomass through Torrefaction

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Abstract

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Biomass is an immense area of renewable energy research involving the use of biological
material for energy purposes. Biomass is readily available and pollutes less that
traditional fossil fuels; however, it has a lower energy density than fossil fuels, making it
economically unfeasible. One possible solution to this problem is torrefaction, the
relatively low-temperature cooking of biomass. It is already known that torrefaction
increases the energy density of biomass by driving off low-energy components such as
water. The goal of this research is to determine what conditions of temperature and time
duration are most effective in increasing the biomass energy level; simply put, the
optimal biomass should be compact with a high energy density. Samples of Vermont
Hardwood are tested by cooking in an oven under a steady flow of nitrogen gas to create
an intert environment. Quality of variable results is determined by mass loss, density, and
chemical composition. Energy density cannot be directly measured as sawdust is not
appropriate use of bomb calorimeter. Mass Loss is calculated by measuring samples
before and after cooking, while density is calculated my measuring the heights and
masses of pellets pressed under fixed load with a constant diameter. Chemical
composition is to be found through analysis of data collected from molecular beam mass
spectrometer (MBMS). The results indicate that, as expected, a higher percentage mass
lost occurs with higher temperature and longer treatment duration with temperature
having a greater impact. Density is found to increase with treatment duration but has no
clear connection with temperature change. The future of the research in this field will
include the analysis of the MBMS data and the determination of the optimal torrefaction
conditions.

Category: **Chemistry/Engineering**

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Introduction

Today, approximately 80% of our nation's energy comes from fossil fuels [4]. Not only do these sources of energy pollute our air with carbon dioxide, nitrogen oxides, sulfur dioxide, and other compounds harmful to the environment and ourselves, but it is arguable that the extraction of fossil fuels is harmful to the environment as well. Growing energy resources in a renewable manner above ground is more logical than mining or drilling for such materials underground. It would make even more sense if these grown resources burned cleaner than the underground ones. Biomass energy is a renewable energy source that fits such specifications. [4]

Biomass is biological material such as plant material, animal or agricultural waste used in the production of energy. This technology makes use of resources already available in plentiful amounts in plant byproducts (such as sawdust from sawmills), animal waste (such as chicken manure) and "energy crops", quick growing plants such as poplar trees and switchgrass grown specifically for use in the energy industry. Biomass is a renewable energy source because, if grown properly, it can be maintained to readily replenish the supply consumed. Concerning pollution, biomass energy is desirable because although it does emit carbon dioxide into our atmosphere, it only gives off as much as it absorbs in the growth of the plant. Additionally, biomass combustion emits less of other pollutants. Theoretically, if a coal-powered fire plant displaces 5% heat input of its coal feed with biomass feed, nitrogen oxide emissions can be reduced by 10% and sulfur dioxide emissions my 5% [4]. Other advantages of biomass include

encouraging growth of rural economy with a new cash crop (energy crops) and extending the life of landfills by using what is normally considered trash for energy production.[4]

Biomass carries some disadvantages. Its energy density is much lower than that of traditional energy resources such as fossil fuels. This low density makes biomass fuel more expensive to transport, store and utilize than the traditionally used fossil fuel. This problem is compounded by the hydrophilic nature of the material. The absorption of moisture causes the biomass to decrease in energy density even further and make its use even more expensive and less feasible on a massive scale. [1,3]

One possible solution to biomass' weaknesses is torrefaction. Torrefaction is the heating of biomass at temperatures between 200-300 degrees Celsius. There are several benefits of this process. The two main points are that the biomass increases energy density by losing materials with low or no energy density (water, for example) and that the biomass becomes hydrophobic and is no longer in danger of losing energy density due to moisture exposure. [1]

In my research, I attempt to determine the optimal conditions for torrefaction based upon temperature and duration of treatment. These wood treated was assessed in fuel quality based on density, mass loss during treatment, energy density and chemical composition.

In conducting this research, the goal is to produce a form of biomass energy feedstock capable of comparing in both economy and performance to traditional fossils fuels. It is hoped that the biomass will reach a quality that can be used in tandem with or in place of fossil fuels.

Materials and Methods

The sample material used in this research was Vermont Hardwood sawdust. We acquired all sawdust from one source and stored the material in four separate Ziploc bags.

The density of raw, untreated sawdust was found by pressing the material into pellets. Pelletization took place in a Carver Hydraulic Laboratory Press with heated platens. The dies used in pelletization were Carver hardened stainless steel dies rated up to a 18,000 lb load with a .5 inch interior diameter. Initially, smaller dies of stainless steel were used in pelletization but became flawed in using a load sufficient to press the pellets. The resulting imperfect pellets were not appropriate for density measurement. A 10,000 lb load was applied to each pellet. All mass measurements in experimentation were conducted using a Mettler AE200 Balance.

The torrefaction was conducted in a laboratory furnace. Temperature was controlled using an OMEGA CN8500 device with an internal thermocouple and monitored using an Omega DP462 device. The methods corresponding to these devices are described later in this section. Sawdust samples were cooked in ceramic boats measuring approximately 2"x3/8"x1/4" placed inside a glass tube inside the furnace. Flowing nitrogen gas through the glass tube at a rate between .5-1.5 liters per minute created an inert environment. The high temperature variation within the tube limited the number of boats cooked at one time to two. The point of optimal temperature accuracy at which the boats were centered was located 6 inches from the right hand side of the furnace. A matrix of torrefaction conditions were tested at temperatures of 200°C, 225°C,

250°C, and 275°C for durations of 5, 10, 20, and 30 minutes. In order to obtain the specific temperature within the glass tube, the thermostat was set at level much lower than the desired temperature. For a temperature of 275°C, the thermostat is set at 214°C; for 250°C, 195°C; for 225°C, 168°C; for 200°C, 142°C. For each temperature and time condition, usually four samples were cooked and measured for mass loss occurring during cooking. Upon analysis of initial data, it was determined testing should be conducted at higher temperatures. Thus, for a temperature of 285°C, the thermostat should be set at 223°C; for 295°C, 232°C. Temperature monitoring conducted with the Omega DP462 and Omega thermocouple, the tip of which was placed approximately 6 inches inside the glass tube with care taken not to touch the tube itself. The resulting density of each condition sample was measured using the same process as for the untreated sawdust.

An attempt was made to use a bomb calorimeter to measure the energy density of the pellets. A Parr 1341 Oxygen Bomb Calorimeter was used in experimentation. A bomb calorimeter is a device in which a pellet sample whose energy content is to be measured is placed inside a heavy metal canister, the bomb. The bomb is filled to 25 atmospheres pressure with oxygen and the sample is detonated with the canister in a water heat sink. Using benzoic acid, the energy content of which is known, one can calculate the heat capacity of the calorimeter. Knowing the heat capacity of the calorimeter and the measured temperature rise resulting from sample combustion, one can determine its energy density. For more details on this process, refer to Operating Instructions for the 1341 Oxygen Bomb Calorimeter. [2]

In order to determine chemical composition of various samples, a molecular beam mass spectrometer (MBMS) analysis was performed. The conditions were 550°C temperature with a flow rate of 5 liters per minute in a single stage reactor.

Results

The system of sample identification runs as follows:

Wood Type-Temperature (°C)-Time Duration (minutes). For example, a sample of Vermont Hardwood sawdust from bag one torrefied at 250°C for 20 minutes would be identified by VH1-250-20.

Density was found as an average of three measurements taken from pelletized samples. The results are listed in Appendix A in spreadsheet format. Measurements were initially taken using both room temperature and heated platen. A nonlinear regression made of the data was plotted in a three-dimensional mesh graph shown as Appendix B. An attempt was made to measure mass loss resulting from pressing pellets on heated platens and dies. This failed as inaccuracy with spilled sawdust made results unrepeatable. Additionally, the hardened steel pellet dies contain plastic and rubber components that could have been damaged by heating; also, heating causes small parts to become impossible to handle using heat protective equipment. As a result, only densities from pellets made on unheated platens are listed.

Percentage mass loss occurring from heating was measured from four individual boats of each sample. Results are documented in spreadsheet form in Appendix C. The mass losses for each sample were averaged in order to determine a time and temperature dependant average. A nonlinear regression was performed on the data and graphed in a three-dimensional mesh plot shown as Appendix D.

Bomb calorimeter data was taken for several samples. Data is obtained from a computer collection program and transferred into a spreadsheet format. Results are based upon the temperature rise occurring after sample combustion. Also, the rate of temperature change before and after this temperature rise is used to calculate the degree to which the calorimeter is not perfectly adiabatic. For further information on calculations, refer to Parr Operating Instructions [2].

Sample ID	Heat Capacity, cal/g
VHI-275-30-B	-5161.45
VHI-275-30-A	-3324.06
VHI-275-30-C	-5292.37
VHI-275-20-A	-3287.13
VHI-275-20-B	-4027.07
VHI-275-20-C	-5621.04
VHI-250-30-A	-5740.5
VHI-250-30-B	-4486.54
VHI-250-30-C	-3886.26
VHI-275-30-B	-5161.45

Table 1: Sample of data for various torrefied sawdust samples and corresponding heat capacities.

Molecular Beam Mass Spectrometer (MBMS) data was also collected. Results are listed in 75 different files and will be analyzed at a later date by NREL researchers.

Discussion and Conclusion

From analysis of density data, it seems apparent that as the duration of treatment increases, the density generally increases as well. Further experimentation is needed to determine what trend exists between temperature and density, if any, as the data collected in this research shows no clear correlation.

In cooking the samples, there is a definite effect of time and temperature on the dependant percentage mass lost: the greater the temperature and the greater the duration

of treatment, the greater the percentage of the sample's mass is lost. Analysis of the data graph in Appendix D indicates temperature has a greater effect on mass lost than time.

The wide variation in the results of the bomb calorimeter experiments listed in Table 1 indicates that the results of this procedure are not reproducible. This sampling of data is a representative example of the type of inaccuracy present in all bombings performed. A device of this sort is better suited to pure chemicals rather than for use with sawdust and other more complex substances.

At this point, no conclusions can be made regarding the MBMS as this data will be analyzed at a later time by other researchers. This information will help us to understand the different processes that occur under each of the conditions tested in my research.

The goal of continuing research is to determine which conditions produce a fuel with optimal chemical composition to result in high energy density in an economical process. In order to achieve this, the MBMS results, mass loss, and density must all be taken into account. Additionally, other variables may at one point be tested, such as the use of a reactive cooking environment such as oxygen or water vapor. The research presented in this paper is intended as a stepping stone from which other researchers and scientists can continue to investigate this field.

Acknowledgements

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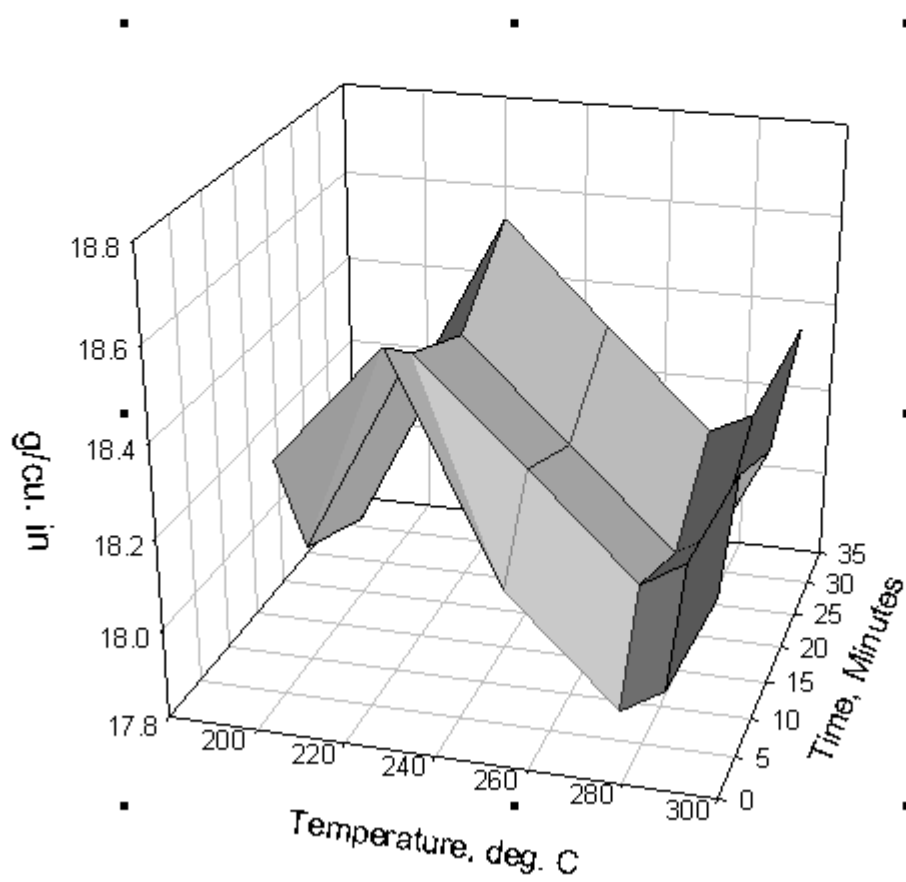
Appendix A

Revised density calculations based upon pellets from hardened steel dies

Pellet ID	Height (in.)	Mass (g)	Diameter (in)	Surface area (in^2)	Volume (in^3)	Density (g/in^3)
VHI-0-0	0.216	0.8168		0.19635	0.0424115	19.25893
VHI-0-0	0.183	0.6895		0.19635	0.03593197	19.18904
VHI-0-0	0.147	0.5165		0.19635	0.02886338	17.89465
VHI-275-30	0.194	0.6894		0.19635	0.03809181	18.09838
VHI-275-30	0.151	0.5301		0.19635	0.02964878	17.87932
VHI-275-30	0.195	0.6874		0.19635	0.03828816	17.95333
VHI-275-20	0.206	0.7366		0.19635	0.04044801	18.21103
VHI-275-20	0.17	0.6248		0.19635	0.03337942	18.71812
VHI-275-20	0.175	0.5945		0.19635	0.03436117	17.30151
VHI-275-10	0.189	0.6902		0.19635	0.03711006	18.59873
VHI-275-10	0.165	0.6102		0.19635	0.03239767	18.83469
VHI-275-10	0.175	0.6286		0.19635	0.03436117	18.29391
VHI-275-10	0.16	0.5676		0.19635	0.03141593	18.06727
VHI-275-5	0.163	0.5635		0.19635	0.03200498	17.60664
VHI-275-5	0.149	0.5054		0.19635	0.02925608	17.27504
VHI-275-5	0.181	0.5956		0.19635	0.03553927	16.75893
VHI-250-30	0.169	0.6198		0.19635	0.03318307	18.6782
VHI-250-30	0.175	0.6224		0.19635	0.03436117	18.11347
VHI-250-30	0.152	0.5379		0.19635	0.02984513	18.02304
VHI-250-20	0.142	0.4841		0.19635	0.02788163	17.36268
VHI-250-20	0.149	0.5345		0.19635	0.02925608	18.26971
VHI-250-20	0.141	0.5092		0.19635	0.02768529	18.39244
VHI-250-10	0.165	0.5864		0.19635	0.03239767	18.10006
VHI-250-10	0.158	0.5501		0.19635	0.03102323	17.73188
VHI-250-5	0.162	0.5696		0.19635	0.03180863	17.90709
VHI-250-5	0.138	0.5146		0.19635	0.02709624	18.99157
VHI-250-5	0.122	0.4406		0.19635	0.02395464	18.39309
VHI-225-30	0.205	0.7505		0.19635	0.04025166	18.6452
VHI-225-30	0.181	0.7062		0.19635	0.03553927	19.87098
VHI-225-30	0.13	0.5133		0.19635	0.02552544	20.10935
VHI-225-20	0.179	0.6525		0.19635	0.03514657	18.56511
VHI-225-20	0.149	0.5365		0.19635	0.02925608	18.33807
VHI-225-20	0.172	0.5761		0.19635	0.03377212	17.05845
VH1-225-10	0.213	0.7628		0.19635	0.04182245	18.23901
VH1-225-10	0.178	0.6358		0.19635	0.03495022	18.19159
VH1-225-10	0.162	0.5729		0.19635	0.03180863	18.01084
VH1-225-5	0.148	0.5269		0.19635	0.02905973	18.13162
VH1-225-5	0.196	0.7137		0.19635	0.03848451	18.54512
VH1-225-5	0.175	0.632		0.19635	0.03436117	18.39285
VHI-200-30	0.155	0.5552		0.19635	0.03043418	18.24265
VHI-200-30	0.125	0.4473		0.19635	0.02454369	18.22464
VHI-200-30	0.088	0.3158		0.19635	0.01727876	18.27677
VH1-200-20	0.184	0.6447		0.19635	0.03612832	17.84473

Appendix A, continued		0.6823	0.19635	0.03750276	18.19333
VH1-200-20	0.154	0.5497	0.19635	0.03023783	18.17922
VH1-200-10	0.198	0.6593	0.19635	0.03887721	16.95852
VH1-200-10	0.16	0.5579	0.19635	0.03141593	17.75851
VH1-200-10	0.142	0.4807	0.19635	0.02788163	17.24074
VH1-200-5	0.14	0.517	0.19635	0.02748894	18.80757
VH1-200-5	0.132	0.4668	0.19635	0.02591814	18.01055
VH1-200-5	0.114	0.4078	0.19635	0.02238385	18.21849
VH2-285-30	0.15	0.5414	0.19635	0.02945243	18.38218
VH2-285-30	0.11	0.3838	0.19635	0.02159845	17.76979
VH2-285-30	0.107	0.3557	0.19635	0.0210094	16.93052
VH2-285-20	0.149	0.5413	0.19635	0.02925608	18.50214
VH2-285-20	0.108	0.3851	0.19635	0.02120575	18.16017
VH2-285-20	0.114	0.4275	0.19635	0.02238385	19.09859
VH2-285-10	0.13	0.4823	0.19635	0.02552544	18.89487
VH2-285-10	0.1	0.3482	0.19635	0.01963495	17.73368
VH2-285-10	0.107	0.3971	0.19635	0.0210094	18.90106
VH2-285-5	0.1	0.372	0.19635	0.01963495	18.9458
VH2-285-5	0.094	0.3208	0.19635	0.01845686	17.38107
VH2-295-30	0.165	0.6052	0.19635	0.03239767	18.68035
VH2-295-30	0.125	0.4216	0.19635	0.02454369	17.17753
VH2-295-30	0.16	0.5762	0.19635	0.03141593	18.34102
VH2-295-20	0.117	0.4283	0.19635	0.0229729	18.64371
VH2-295-20	0.17	0.5991	0.19635	0.03337942	17.94818
VH2-295-20	0.14	0.4942	0.19635	0.02748894	17.97814
VH2-295-10	0.105	0.3822	0.19635	0.0206167	18.53837
VH2-295-10	0.11	0.4233	0.19635	0.02159845	19.59863
VH2-295-10	0.098	0.3519	0.19635	0.01924226	18.28788
VH2-295-5	0.168	0.616	0.19635	0.03298672	18.67418
VH2-295-5	0.131	0.4629	0.19635	0.02572179	17.99641
VH2-295-5	0.1	0.3277	0.19635	0.01963495	16.68962

Appendix B

Density

Appendix C

Mass Loss Data for Torrefied Biomass, Emily Brooking, 6/2002, Lab Book 2494
Heat Type Key:

        VHI - Biomass Type/Batch (Vermont Hardwood, Batch 1)
        175- Temperature Cooked at in degrees C
        60- Duration of Cooking Period in Minutes

Heat Type	Raw Biomass	Cooked Biomass	Amt. Reduced	Percentage Reduced
VHI-250-30	1.1551	0.9983	0.1568	13.57458
VHI-250-30	1.1291	0.9998	0.1293	11.4516
VHI-250-30	1.1318	0.9624	0.1694	14.96731
VHI-250-30	1.1581	0.9965	0.1616	13.95389
VHI-250-10	1.0218	0.9345	0.0873	8.543746
VHI-250-10	1.1471	1.0355	0.1116	9.728882
VHI-250-10	1.0875	1.0166	0.0709	6.51954
VHI-250-10	1.063	0.9858	0.0772	7.262465
VHI-250-5	1.1711	1.1114	0.0597	5.097771
VHI-250-5	1.1927	1.1312	0.0615	5.156368
VHI-250-20	1.1443	0.9867	0.1576	13.77261
VHI-250-20	1.1808	1.0303	0.1505	12.7456
VHI-250-20	1.1487	1.0175	0.1312	11.42161
VHI-250-20	1.3154	1.174	0.1414	10.74958
VHI-275-30	1.2665	0.9908	0.2757	21.76865
VHI-275-30	1.2911	0.9668	0.3243	25.11812
VHI-275-30	1.2914	0.9904	0.301	23.30804
VHI-275-30	1.2855	0.9661	0.3194	24.84636
VHI-275-30	1.0807	0.8043	0.2764	25.57602
VHI-275-30	1.1203	0.849	0.2713	24.21673
VHI-275-30	1.1715	0.8681	0.3034	25.89842
VHI-275-30	1.193	0.9115	0.2815	23.59598
VHI-275-30	1.2297	0.9535	0.2762	22.46076
VHI-275-30	1.2255	0.9435	0.282	23.01102
VHI-275-30	1.1586	0.9102	0.2484	21.43967
VHI-275-30	1.1527	0.8881	0.2646	22.9548
VHI-275-20	1.1404	0.9281	0.2123	18.61627
VHI-275-20	1.1244	0.8699	0.2545	22.63429
VHI-275-20	1.1961	0.9703	0.2258	18.87802
VHI-275-20	1.2509	0.971	0.2799	22.37589
VHI-275-10	1.172	1.0098	0.1622	13.83959
VHI-275-10	1.1449	1.0175	0.1274	11.12761
VHI-275-10	1.065	0.9596	0.1054	9.896714
VHI-275-10	1.0283	0.8776	0.1507	14.65526
VHI-275-5	1.092	1.0043	0.0877	8.031136
VHI-275-5	1.1432	1.0803	0.0629	5.502099
VHI-225-30	1.15	1.0693	0.0807	7.017391
VHI-225-30	1.2784	1.1958	0.0826	6.461202

VHI-225-30	1.2349	1.1384	0.0965	7.814398
VHI-225-30	1.2994	1.2131	0.0863	6.641527
VHI-225-20	1.239	1.1545	0.0845	6.820016
VHI-225-20	1.3502	1.2639	0.0863	6.391646
VHI-225-20	1.2687	1.1834	0.0853	6.723418
VHI-225-20	1.2098	1.1319	0.0779	6.439081
VHI-225-10	1.1315	1.0747	0.0568	5.019885
VHI-225-10	1.3312	1.261	0.0702	5.273437
VHI-225-10	1.1063	1.0508	0.0555	5.016722
VHI-225-10	1.0372	0.9829	0.0543	5.235249
VHI-225-5	1.0208	0.9726	0.0482	4.721787
VHI-225-5	1.2176	1.1602	0.0574	4.714192
VHI-225-5	1.0451	0.9838	0.0613	5.865467
VHI-225-5	1.2063	1.1467	0.0596	4.940728
VHI-200-30	1.1574	1.093	0.0644	5.564196
VHI-200-30	1.0442	0.9847	0.0595	5.698142
VHI-200-30	1.102	1.037	0.065	5.898367
VHI-200-30	1.2256	1.1577	0.0679	5.540144
VHI-200-20	1.2142	1.1469	0.0673	5.542744
VHI-200-20	1.1117	1.0497	0.062	5.577044
VHI-200-20	1.1287	1.0679	0.0608	5.386728
VHI-200-20	1.0988	1.0392	0.0596	5.424099
VHI-200-10	1.3039	1.2371	0.0668	5.123092
VHI-200-10	1.1323	1.0736	0.0587	5.184138
VHI-200-10	1.1856	1.1236	0.062	5.22942
VHI-200-10	1.1983	1.1349	0.0634	5.290829
VHI-200-5	1.1389	1.0822	0.0567	4.978488
VHI-200-5	1.1618	1.1019	0.0599	5.155793
VHI-200-5	0.9559	0.9066	0.0493	5.157443
VH2-285-30	1.3452	0.994	0.3512	26.10764
VH2-285-30	1.1541	0.8199	0.3342	28.95763
VH2-285-30	1.3262	0.9854	0.3408	25.69748
VH2-285-30	1.3933	0.9954	0.3979	28.5581
VH2-285-20	1.2583	0.9366	0.3217	25.56624
VH2-285-20	1.3116	1.009	0.3026	23.07106
VH2-285-20	1.2729	0.9482	0.3247	25.50868
VH2-285-20	1.2244	0.9366	0.2878	23.50539
VH2-285-10	1.3406	1.1285	0.2121	15.82127
VH2-285-10	1.2886	1.056	0.2326	18.0506
VH2-285-10	1.2018	0.9822	0.2196	18.27259
VH2-285-10	1.2375	1.0587	0.1788	14.44848
VH2-285-5	1.1624	1.0675	0.0949	8.164143
VH2-285-5	1.3334	1.2381	0.0953	7.147143
VH2-295-30	1.3753	0.9306	0.4447	32.33476
VH2-295-30	1.2989	0.8579	0.441	33.95181
VH2-295-30	1.1719	0.759	0.4129	35.23338
VH2-295-30	1.2841	0.8614	0.4227	32.918

Appendix C

VH2-295-20	1.2616	0.8611	0.4005	31.7454
VH2-295-20	1.3441	0.9464	0.3977	29.58857
VH2-295-20	1.4742	1.0386	0.4356	29.54823
VH2-295-20	1.3031	0.9541	0.349	26.78229
VH2-295-10	1.2656	1.0165	0.2491	19.68236
VH2-295-10	1.1166	0.9214	0.1952	17.48164
VH2-295-5	1.4522	1.3247	0.1275	8.779782
VH2-295-5	1.1276	1.0399	0.0877	7.777581

Appendix D

Percentage Mass Lost in Torrefied Wood